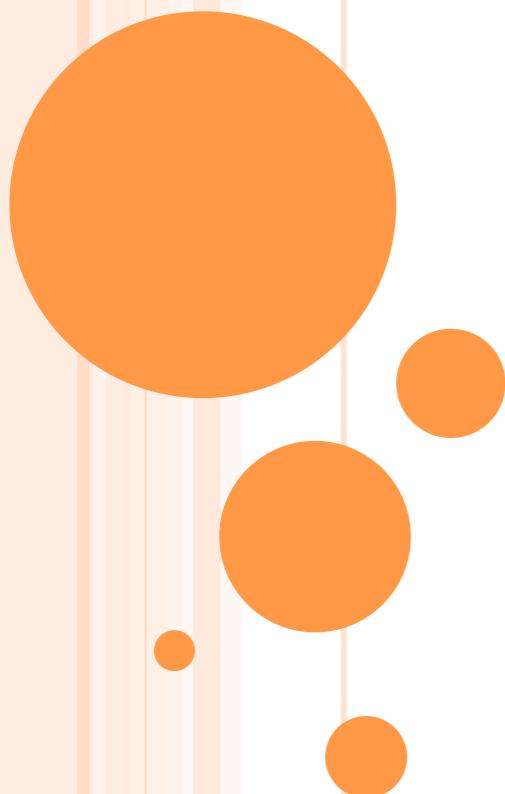


SUSY 2011

Sept., 2011

DARK LIGHT HIGGS



Tao Liu
UC@ Santa Barbara



`` Dark Light Higgs ''

A Supersymmetric Scenario Characterized by Novel Dark Matter and Higgs Physics

ArXiv:1009.3963[hep-ph]

(Phys. Rev. Lett. 106 (2011))

ArXiv:11xx.xxxx[hep-ph]

....

....

In collaboration with

P. Draper (UC, Santa Cruz), J.R. Huang (UC, Irvine),
S.F. Su (Arizona Univ.), C. Wagner (Univ. of Chicago), L.-T. Wang (Univ. of Chicago)
F. Yu (Fermi Lab), H. Zhang (Peking Univ./Univ. of Chicago)

2



``Dark Light Higgs''

A Supersymmetric Scenario Characterized by Novel Dark Matter and Higgs Physics

- What is the ``Dark Light Higgs'' Scenario
- Supersymmetric Light Dark Matter
- Non-standard Higgs Physics
- Conclusions

2



- ☒ What is the ``Dark Light Higgs'' Scenario
- ☒ Supersymmetric Light Dark Matter
- ☒ Non-standard Higgs Physics
- ☒ Conclusions

3



Two Approximate Global Symmetries in the NMSSM

$$W_{NMSSM} = Y_U \mathbf{Q} \mathbf{H}_u \mathbf{U}^c - Y_D \mathbf{Q} \mathbf{H}_d \mathbf{D}^c - Y_E \mathbf{L} \mathbf{H}_d \mathbf{E}^c + \lambda \mathbf{N} \mathbf{H}_u \mathbf{H}_d + \frac{1}{3} \kappa \mathbf{N}^3$$
$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_N^2 |N|^2 - (\lambda A_\lambda H_u H_d N + \text{h.c.}) + \left(\frac{\kappa}{3} A_\kappa N^3 + \text{h.c.} \right)$$

☒ R-symmetry

$$H_u \rightarrow H_u \exp(i\phi_R), \quad H_d \rightarrow H_d \exp(i\phi_R), \quad N \rightarrow N \exp(i\phi_R)$$

- ☒ Explicitly broken by trilinear soft terms in the Higgs sector.
- ☒ Pecci-Quinn (PQ) symmetry

$$H_u \rightarrow H_u \exp(i\phi_{PQ}), \quad H_d \rightarrow H_d \exp(i\phi_{PQ}), \quad N \rightarrow N \exp(-2i\phi_{PQ})$$

- ☒ Explicitly broken by cubic term and its correspondent soft SUSY-breaking term in the Higgs sector.
- ☒ Three CP-even mass eigenstates (h_1, h_2, h_3) and two CP-odd ones (a_1, a_2)
- ☒ In the symmetry limits, $m a_1 \ll \text{EW scale}$ (pseudo - Goldstone boson)

4



Old Story

- ☒ Almost all old studies were focused on the R-symmetry limit (B. A. Dobrescu et al., Phys. Rev. D 63 (2001); R. Dermisek et al., Phys. Rev. Lett. 95 (2005))
- ☒ a_1 is light \ll EW scale (pseudo - Goldstone boson);
- ☒ h_1 is the SM-like Higgs boson;
- ☒ $h_1 \rightarrow a_1 a_1 \rightarrow 4$ fermions is typically dominant, allowing h_1 to be as light as below 100 GeV and hence relaxing the little hierarchy tension
- ☒ Dark matter candidate (χ_1) is typically of EW scale



What is the ``Dark Light Higgs'' Scenario?

Nearly PQ limit: $\kappa/\lambda \rightarrow 0$,
 $A_\kappa \rightarrow 0$

+ Moderate or small λ : $\lambda < \text{or } \sim 0.1$

P. Draper, T.L., C. Wagner, L.T. Wang and H. Zhang, Phys. Rev. Lett. 106 (2011)



Mass of the Lightest Higgs Scalar

Tree-level contribution

$$m_{h_1}^2 \approx -4\varepsilon^2 v^2 + \frac{4\lambda^2 v^2}{\tan^2 \beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2}$$

with $\varepsilon = \frac{\lambda \mu}{m_Z} \left(\frac{A_\lambda}{\mu \tan \beta} - 1 \right)$ being a measure of the deviation of the soft parameter A_λ from $\mu * \tan \beta$

Loop correction

$$\Delta m_{h_1}^2 \approx \frac{\lambda^2 \mu^2}{2\pi^2} \log \frac{\mu^2 \tan^3 \beta}{m_Z^2}$$

Vacuum stability sets a small upper bound

$$\varepsilon_{\max}^2 \approx \frac{1}{4v^2} \left(\frac{4\lambda^2 v^2}{\tan^2 \beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} + \frac{\lambda^2 \mu^2}{2\pi^2} \log \frac{\mu^2 \tan^3 \beta}{m_Z^3} \right)$$

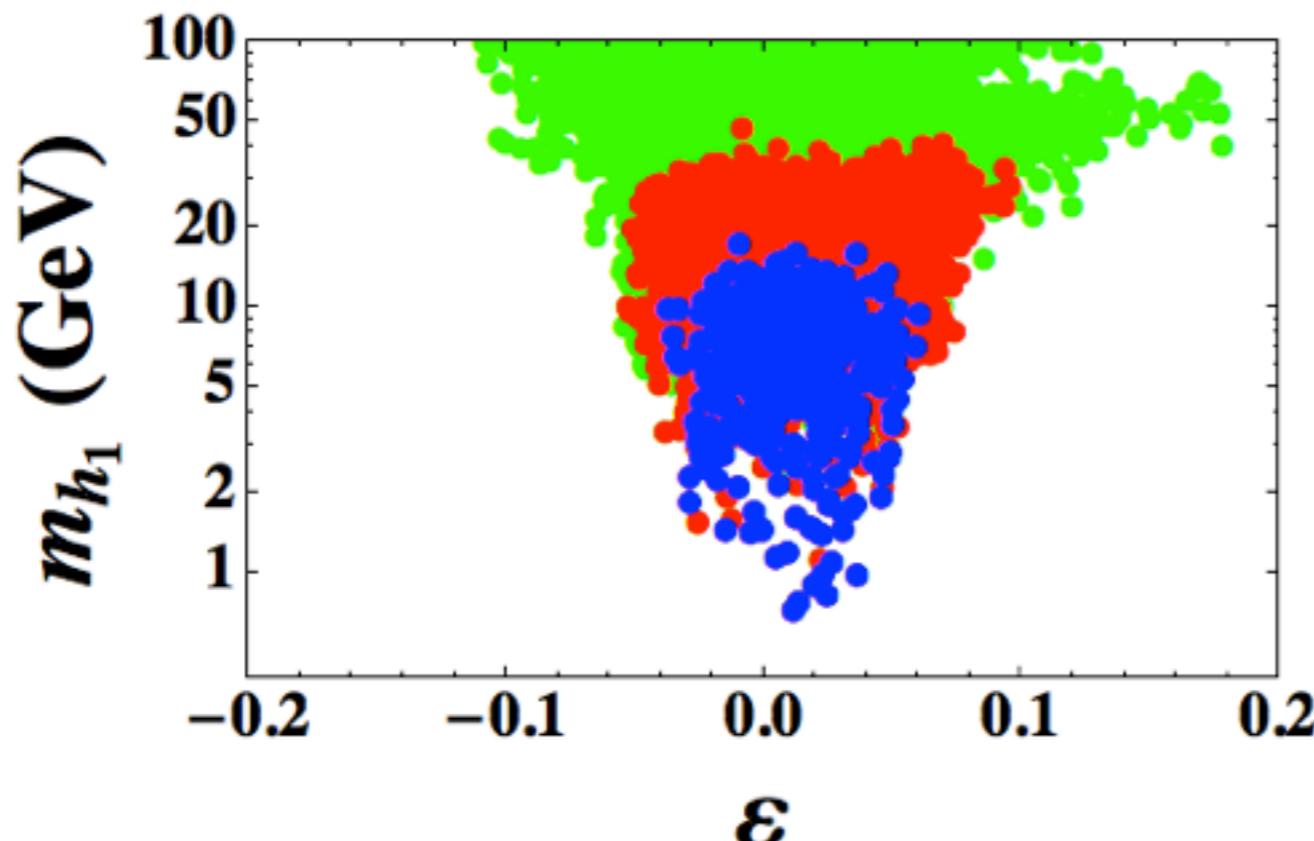
mh1^2 is generically small

7



Mass of the Lightest Higgs Scalar (cd.)

(NMSSMTools 2.3.1 + MicrOMEGAS



P. Draper, T.L., C. Wagner,
L.T. Wang and H. Zhang,
Phys. Rev. Lett. 106 (2011)

$5 \leq \tan \beta \leq 50, 0.05 \leq \lambda \leq 0.5, 0.0005 \leq \kappa \leq 0.05, -0.8 \leq \varepsilon' \leq 0.8, -40\text{GeV} \leq A_\kappa \leq 0, 0.1\text{TeV} \leq \mu \leq 1\text{TeV}$

$\lambda < 0.30, \kappa/\lambda < 0.05, \mu < 400\text{GeV}$

$\lambda < 0.15, \kappa/\lambda < 0.03, \mu < 250\text{GeV}$

- ☒ No point for an epsilon far away from 0 -- vacua are not stable!
- ☒ Blue and red points have a mass range $0.1 \sim 10$ GeV -- the ``DLH'' scenario.

8



Mass of the Lightest Higgs Pseudoscalar and Neutralino

- ☒ A light CP-odd Higgs a_1

$$m_{a_1}^2 \approx -\frac{3\kappa A_\kappa \mu}{\lambda}$$

- ☒ A light lightest neutralino χ_1

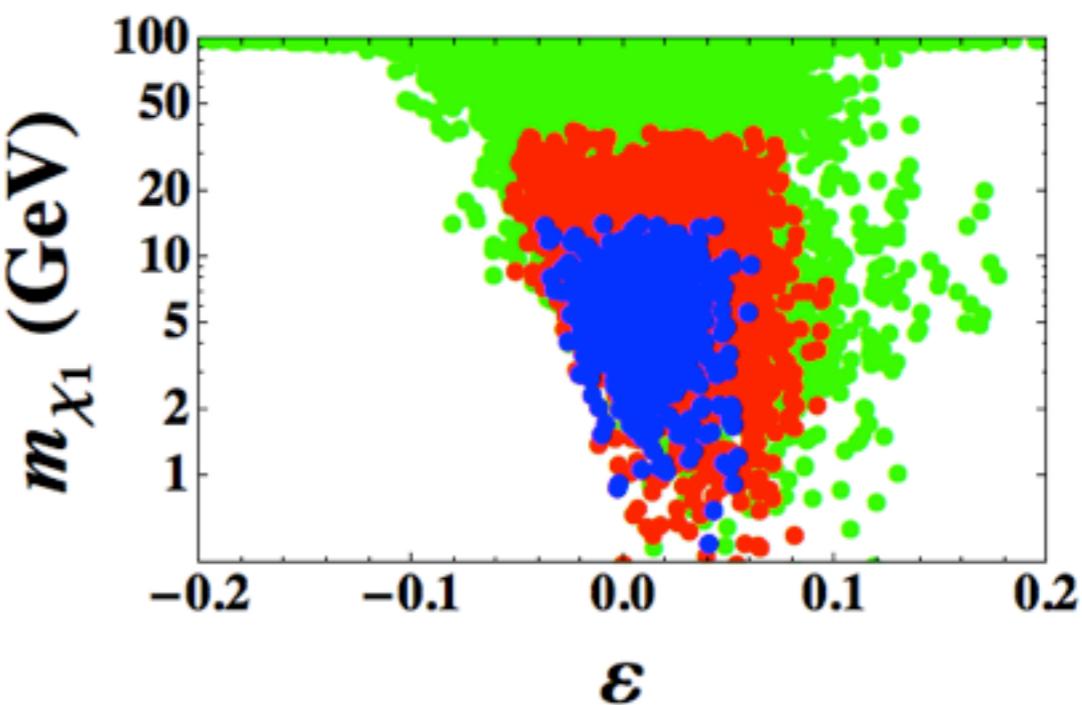
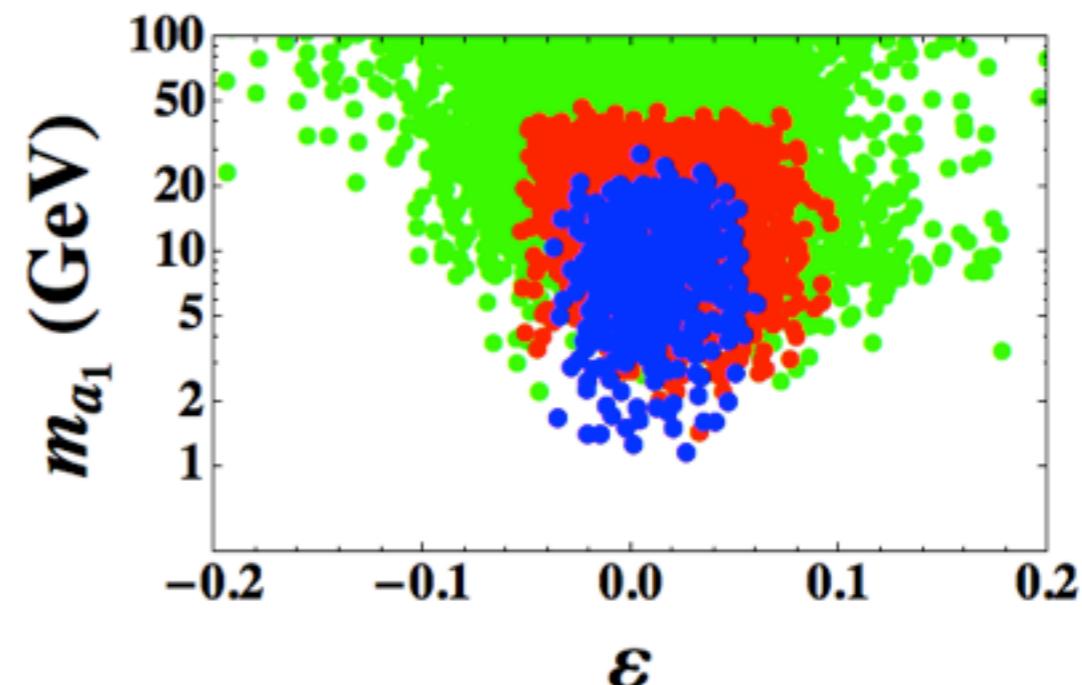
$$m_{\chi_1} \approx \frac{\lambda^2 v^2}{\mu} \sin 2\beta + \frac{2\kappa \mu}{\lambda}$$

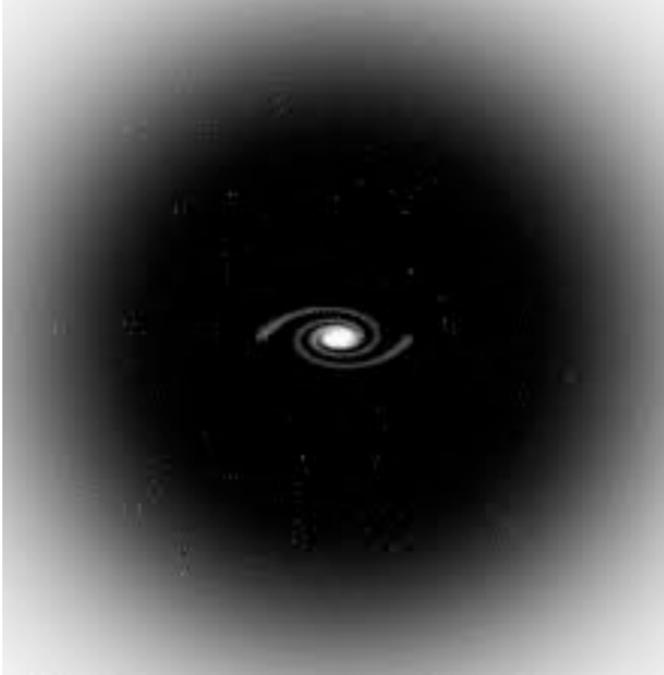
- ☒ Lambda is not large, $\Rightarrow h_1, a_1$ and χ_1 are singlet-like or singlino-like

- ☒ h_2 is SM-like

$$h_2 \sim h_u + h_d \cot \beta - \frac{2\varepsilon v m_Z}{m_Z^2 + \mu^2} h_n$$

- ☒ Comparison: in the R-symmetry limit, h_1 and χ_1 are typically not so light and h_1 is SM-like



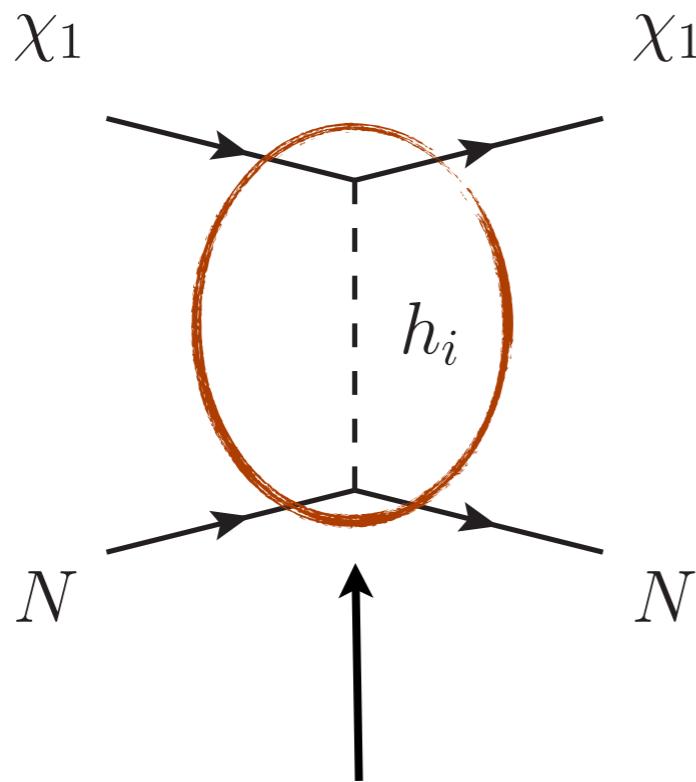


- ☒ What is the ``Dark Light Higgs'' Scenario
- ☒ Supersymmetric Light Dark Matter
- ☒ Non-standard Higgs Physics
- ☒ Conclusions

10

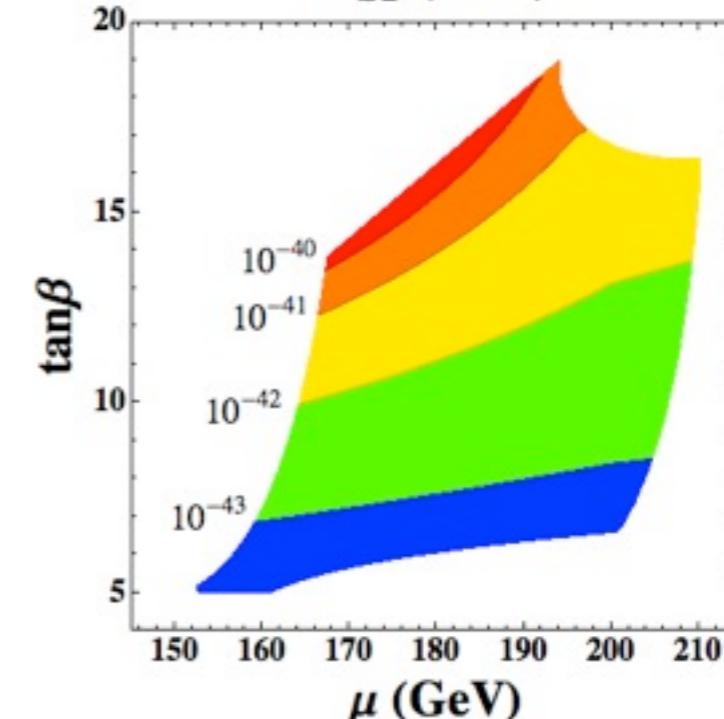
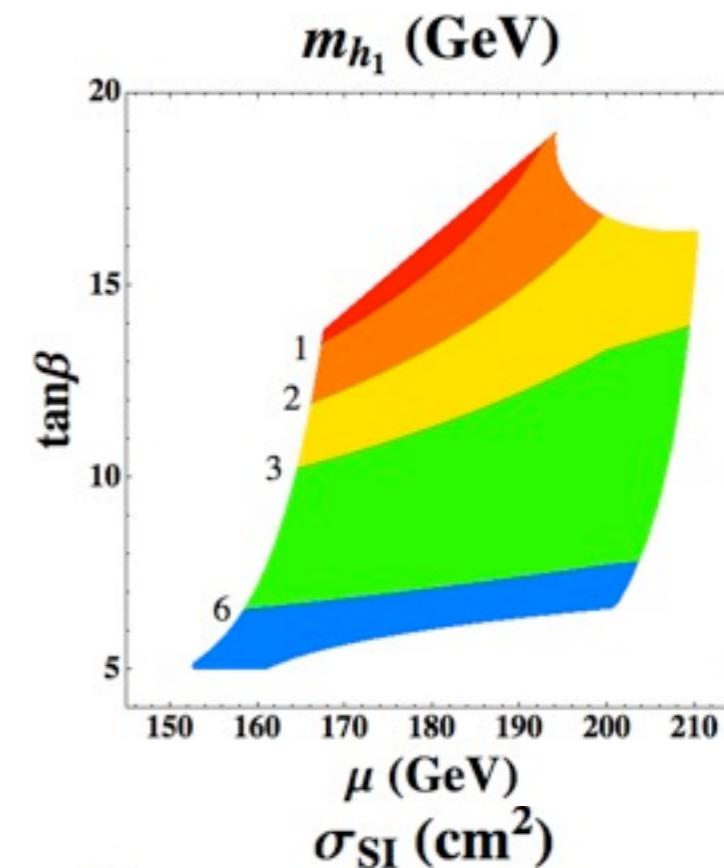


A Novel Supersymmetric Light DM Scenario !



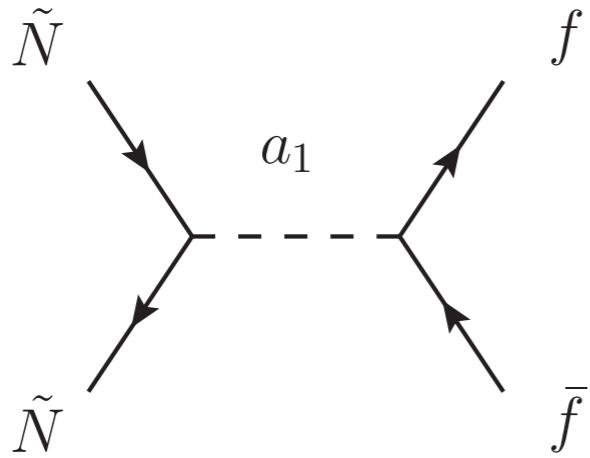
a t-channel process is dominant in spin-independent direct-detection \Rightarrow section be strongly enhanced by a small m_{h_1}

$$\sigma_{\text{SI}} \approx \frac{\left[\left(\frac{\varepsilon}{0.04} \right) + 0.46 \left(\frac{\lambda}{0.1} \right) \left(\frac{v}{\mu} \right) \right]^2 \left(\frac{y_{h_1 \chi_1 \chi_1}}{0.003} \right)^2}{\left(\frac{m_{h_1}}{1 \text{ GeV}} \right)^4} \times 10^{-40} \text{ cm}^2$$





Breit-Wigner Effect => Right Relic Density



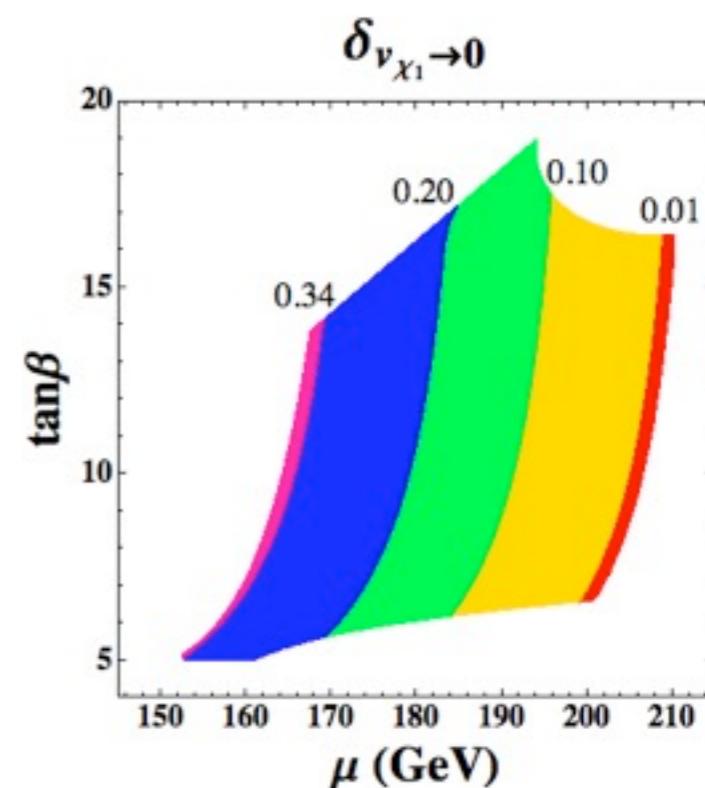
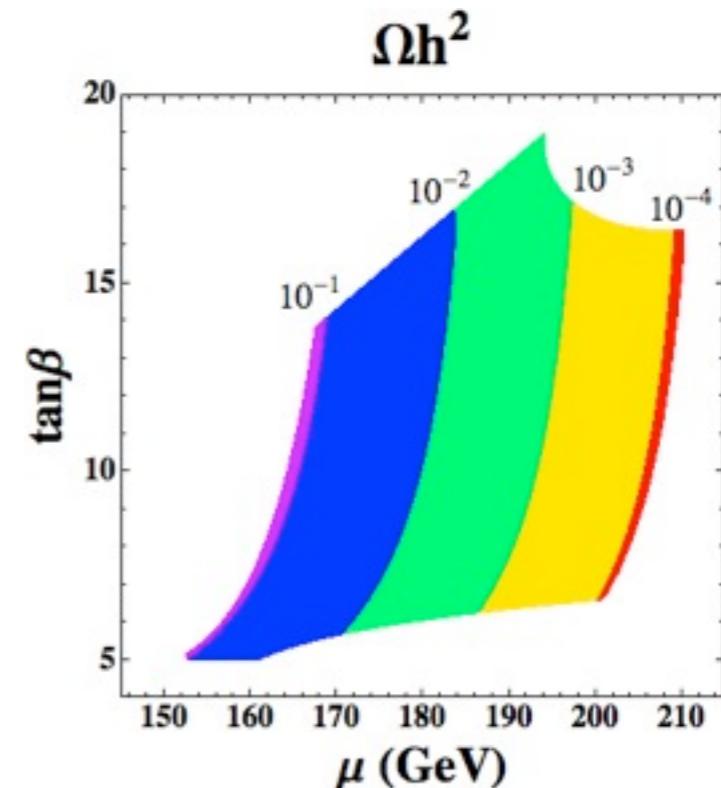
Thermal average of the LSP annihilation cross section

$$\sigma_{f\bar{f}} v_{\chi_1} \approx \frac{3 |y_{a_1 \chi_1 \chi_1} y_{a_1 f\bar{f}}|^2 (1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left| \frac{\Gamma_{a_1} m_{a_1}}{4m_{\chi_1}^2} \right|^2 \right)}$$

$$\delta \equiv |(1 - v_{\chi_1}^2/4)^{-1} - m_{a_1}^2/(4m_{\chi_1}^2)|$$

Relic density

$$\Omega h^2 \approx \frac{0.1 \left(\frac{m_{a_1}}{15 \text{ GeV}} \right) \left(\frac{\Gamma_{a_1}}{10^{-5} \text{ GeV}} \right) \left(\frac{\mu}{v} \right)^2 \left(\frac{0.003}{\kappa} \right)^2 \left(\frac{0.1}{\lambda} \right)^2}{\text{erfc} \left(\frac{2m_{\chi_1}}{m_{a_1}} \sqrt{x_f \delta_{v_{\chi_1} \rightarrow 0}} \right) / \text{erfc}(2.2)}$$



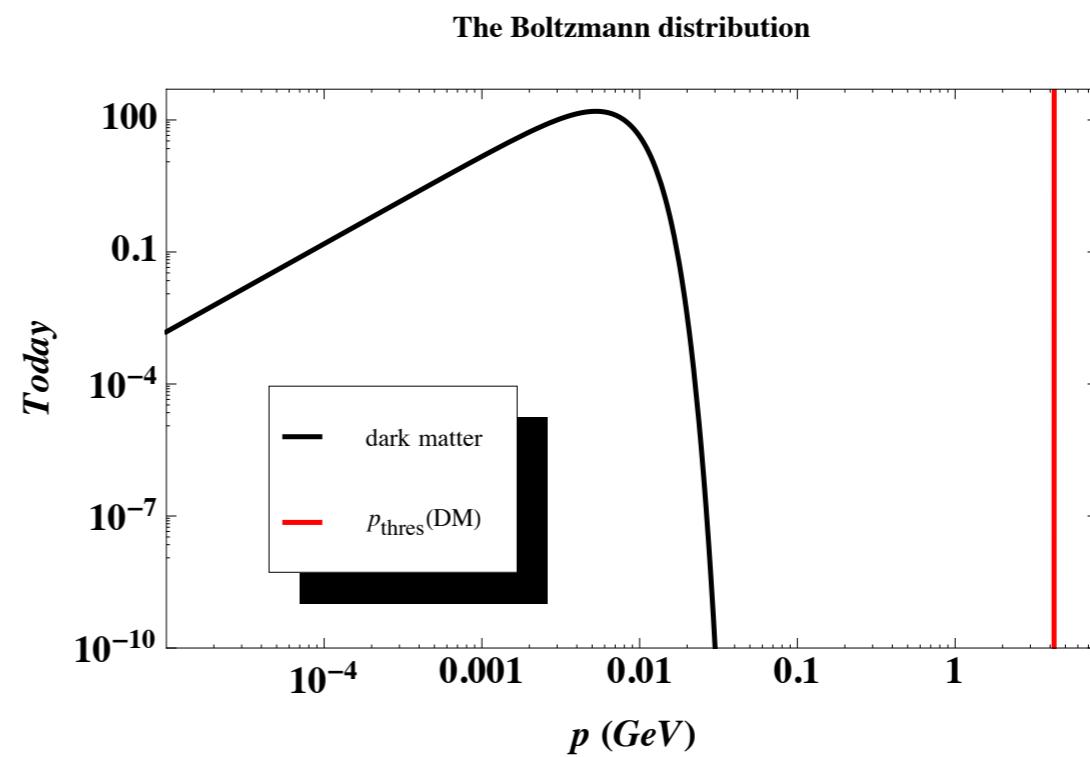
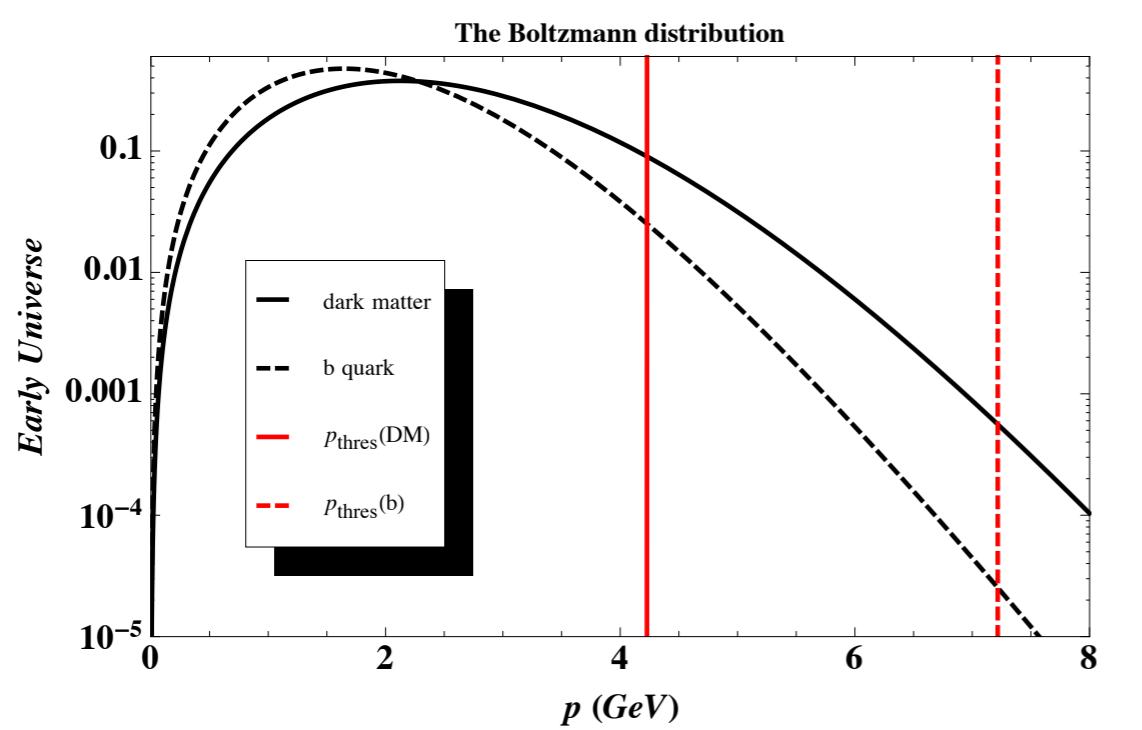
12



No Strong Constraints from Cosmic Ray Exps.

- ☒ Bounds from indirect searches, e.g., Proton spectrum (O. Adriani etc., Nature Vol 458 607 (2009); O. Adriani etc., Phys Rev Lett 105, 121101 (2010)); gamma ray spectrum (Fermi LAT Collaboration, Phys Rev Lett 104, 101101 (2010))

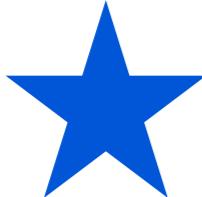
$$\langle \sigma v \rangle_{\text{today}} \ll \langle \sigma v \rangle_{\text{freezing out}}$$



Resonance region (red solid line): dark matter particles in this region has a $\delta \sim 0$, maximizing their annihilation

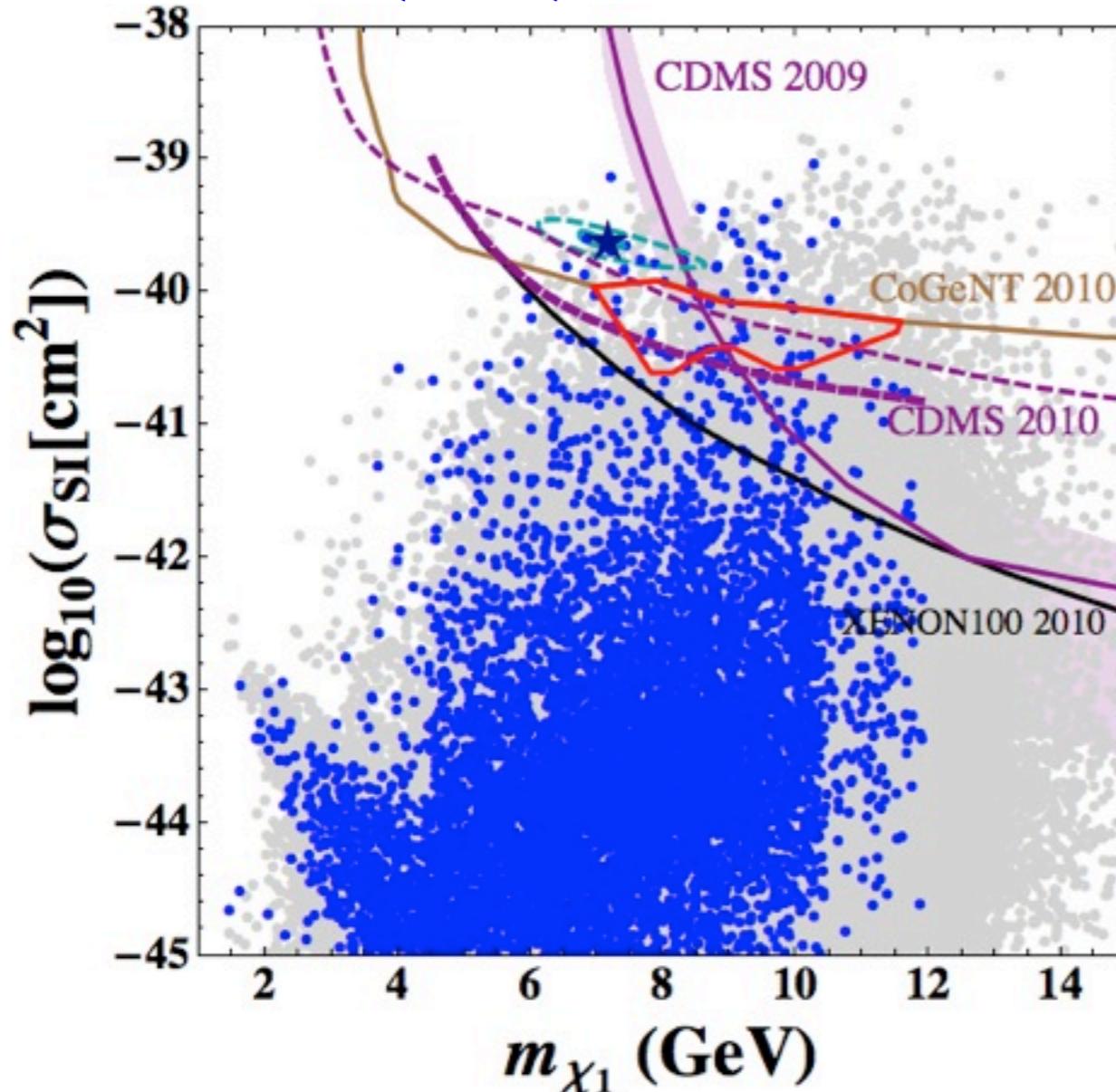


Numerical Results



λ	$\kappa(10^{-3})$	$A_\lambda(10^3)$	A_κ	μ	$\tan \beta$	m_{h_1}
0.1205	2.720	2.661	-24.03	168.0	13.77	0.811
m_{a_1}	m_{χ_1}	m_{h_2}	Brhh	Braa	Ωh^2	$\sigma_{\text{SI}}(10^{-40})$
16.7	7.20	116	0.158%	0.310%	0.112	2.34

$$0.09 \leq \Omega h^2 \leq 0.13$$



$0.05 \leq \lambda \leq 0.15, \quad 0.001 \leq \kappa \leq 0.005,$
 $|\varepsilon'| \leq 0.25, \quad -30\text{GeV} \leq A_\kappa \leq -15\text{GeV},$
 $5 \leq \tan \beta \leq 50, \quad 100\text{GeV} \leq \mu \leq 250\text{GeV}$

- ☒ All points have passed the current exp. bounds of flavor physics, meson decays, and collider exp.
- ☒ The blue points fall in a 3 sigma range of the observed relic density.
- ☒ Their Sigma_SI can be as large as above 10^{-40} cm^2

14



Why Is This Supersymmetric Light DM Scenario Special ?

- ☒ ``One thing we know for sure: such large cross sections can not be realized within the MSSM'', Kathryn Zurek, PCTS Workshop, ``Dark Matter: Direct Detection and Theoretical Developments'', Princeton, Nov. 2010
- ☒ ``If COGENT excess were caused by Dark Matter, we would know only one thing : Within the NMSSM, we would know that the Dark Matter is not singlino-like. The cross section is simply too small'', Ulrich Ellwanger, Plenary Talk, SUSY 2010
- ☒ ``After imposing LEP and B-physics constraints the lightest neutralino is always bino-like and elastic cross sections as large as required by CoGeNT and DAMA/LIBRA are not possible in the NMSSM.'', J. F. Gunion et. al., arXiv:1009.2555 [hep-ph]



The War in Dark Matter World

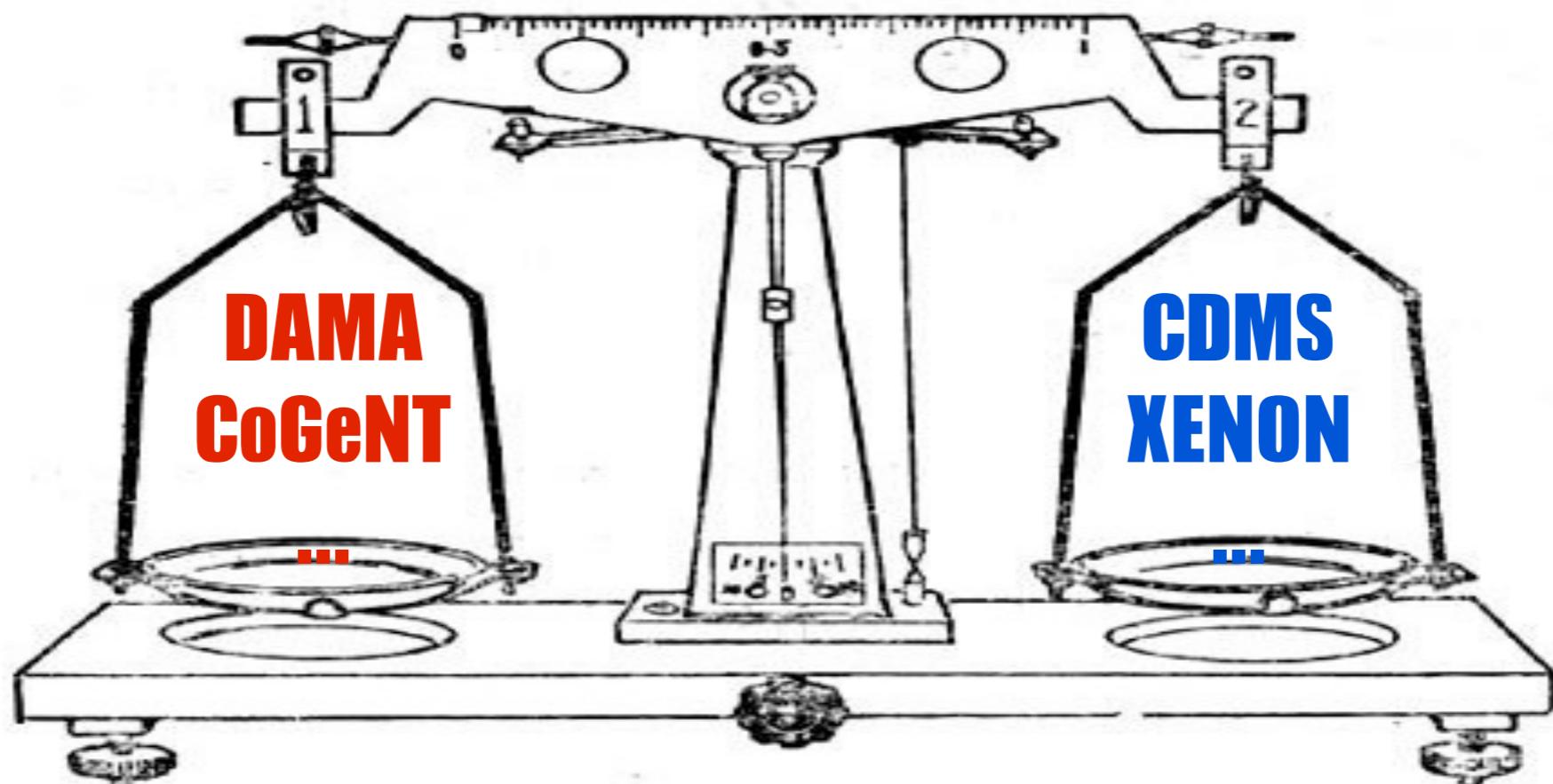
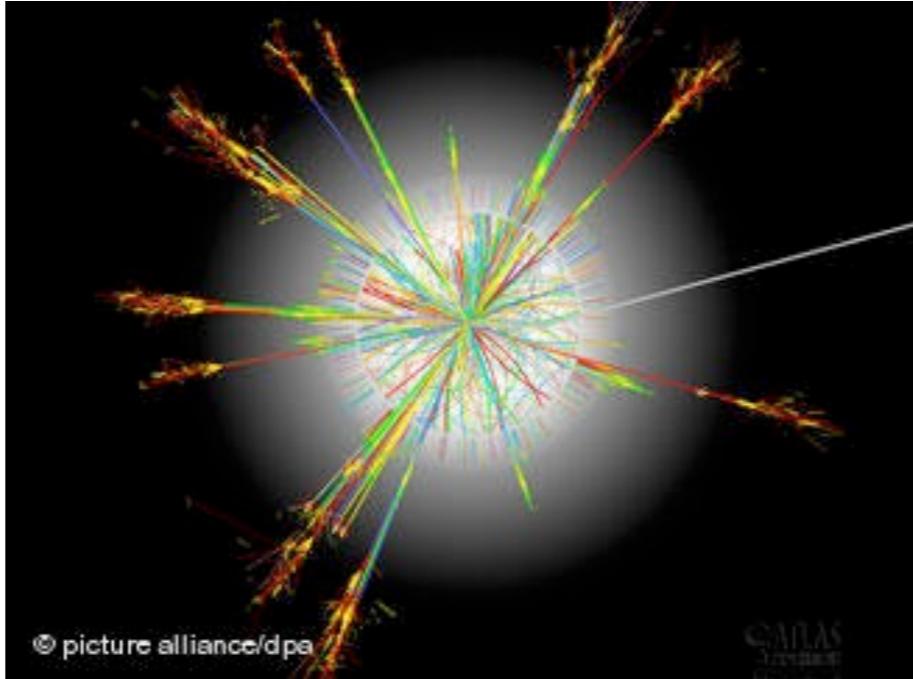


图 1.5-1

- (1) Changes the idea that supersymmetry is incompatible with a light ($\sim O(1)$ GeV) DM scenario characterized by a large cross section of spin-independent direct-detection (10^{-40} cm^2), without violating current exp. bounds
- (2) Provides a supersymmetric light DM scenario accessible to the current direct detections or the ones in the near future

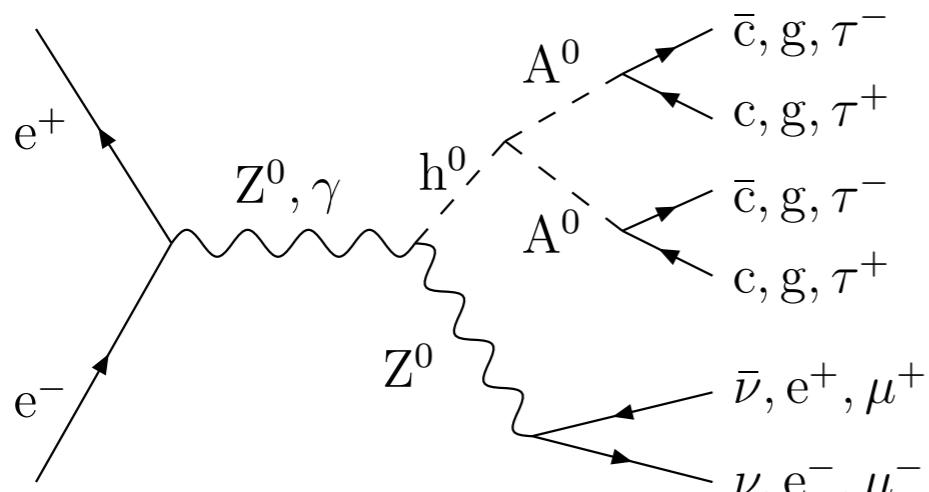


- ☒ What is the ``Dark Light Higgs'' Scenario
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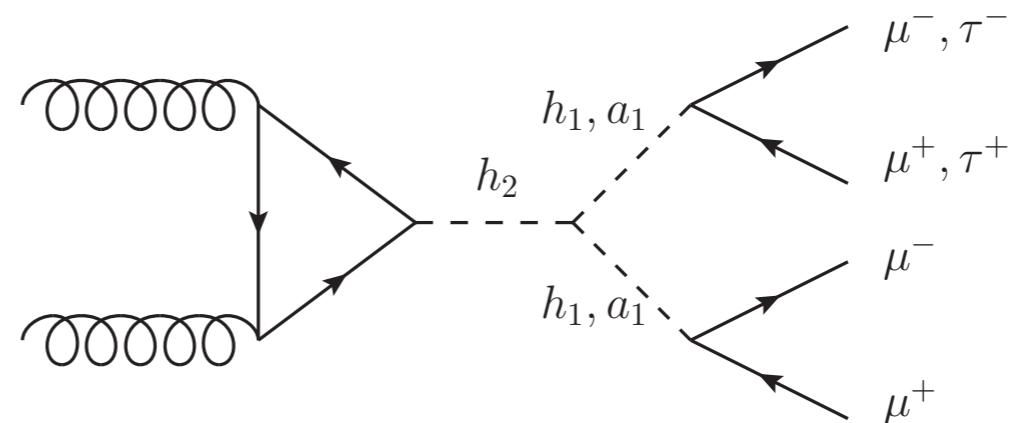
17



Searching for Light Higgs Pair Decays of a SM-like Higgs Boson



- ☒ Motivated by the studies in the R-symmetry limit
- ☒ LEP searches: (1) $(h \rightarrow aa)a \rightarrow 6b$ (**S.** Schael et al. [ALEPH, DELPHI, L3, and OPAL Collaborations], Eur. Phys. J. C 47 (2006); S. Schael et al. [ALEPH Collaboration], JHEP 1005 (2010)); (2) Z -associated Higgs production, with Z leptonically decayed (**S. Schael et al.** [ALEPH Collaboration], JHEP 1005 (2010); **G. Abbiendi et al.** [The OPAL Collaboration], Eur. Phys. J. C 27, (2003)).
- ☒ Tevatron searches: $h_{SM} \rightarrow a_1 a_1$, $h_1 h_1 \rightarrow 4\mu, 2\mu 2\tau$ (**V. M. Abazov et al.** [DO Collaboration], Phys. Rev. Lett. 103 (2009))



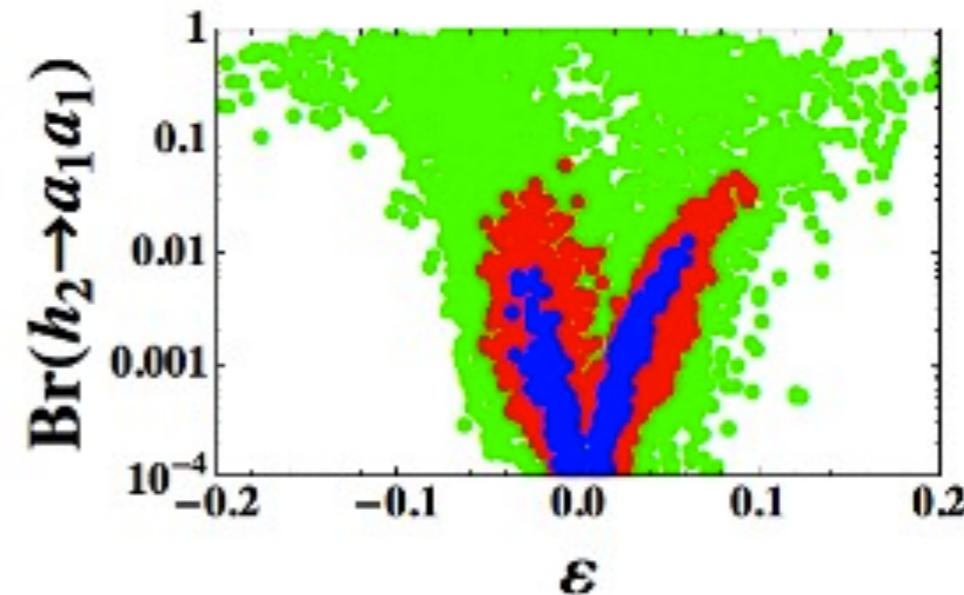
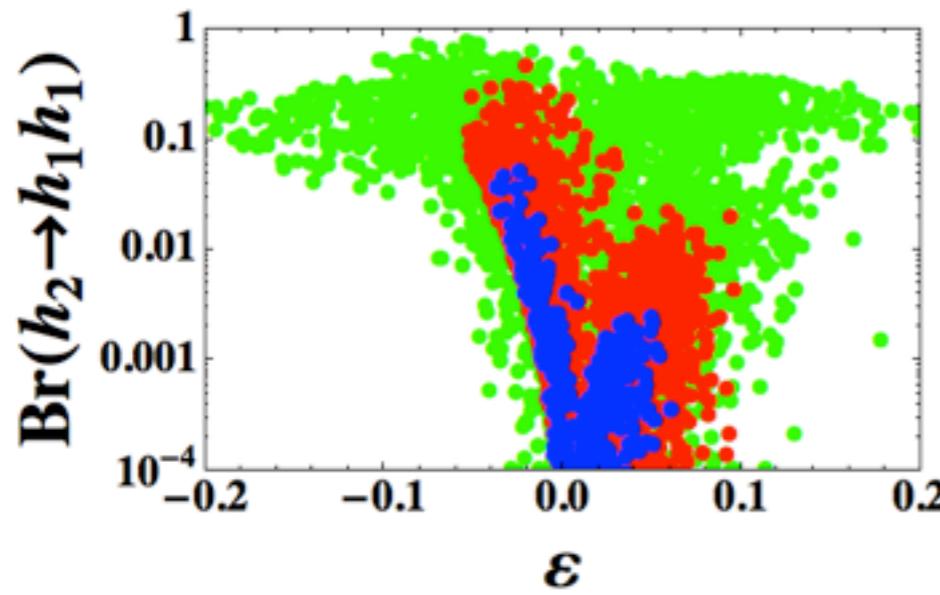
18



Story in the DLH Scenario

- Such decays are kinematically allowed in the DLH scenario
- Leading-order couplings between h_2 and $h_1 h_1$, $a_1 a_1$ are generically suppressed

$$|y_{h_2 h_1 h_1}| = |y_{h_2 a_1 a_1}| = \frac{\lambda v m_Z \varepsilon}{\sqrt{2} \mu}$$



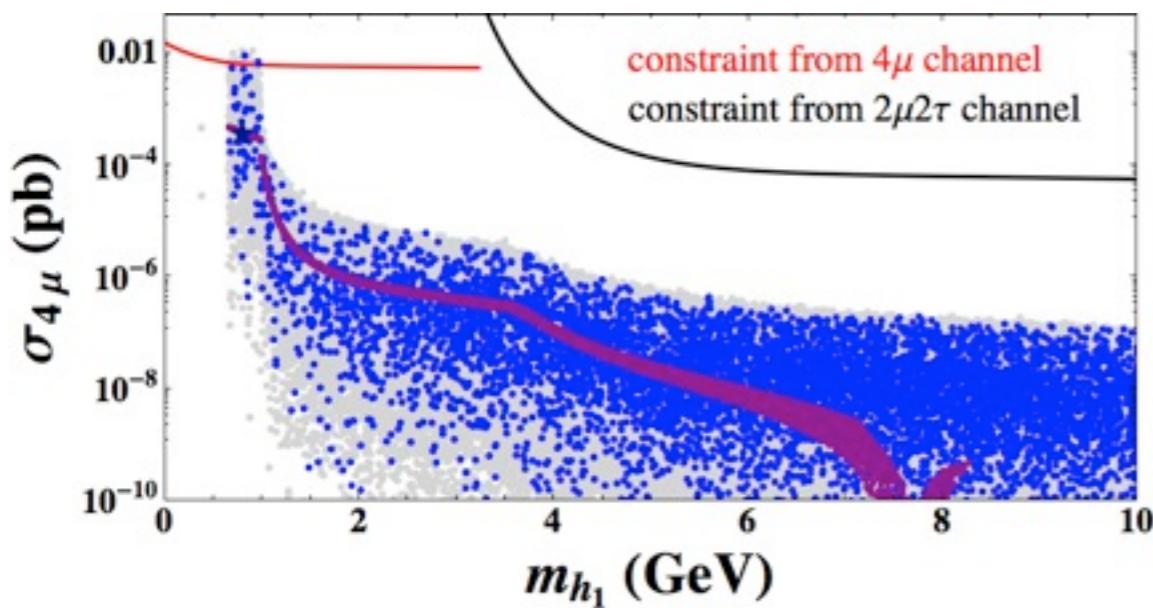
19



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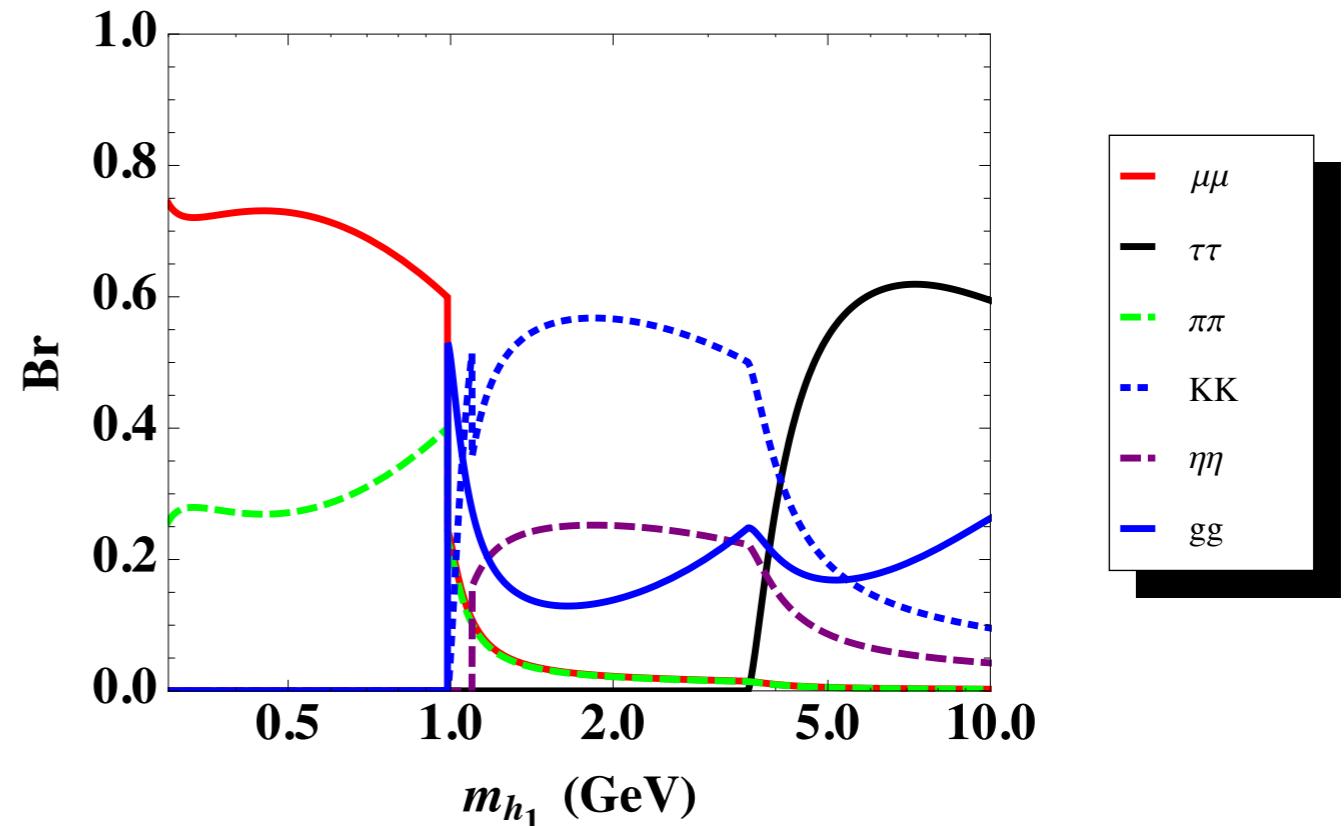
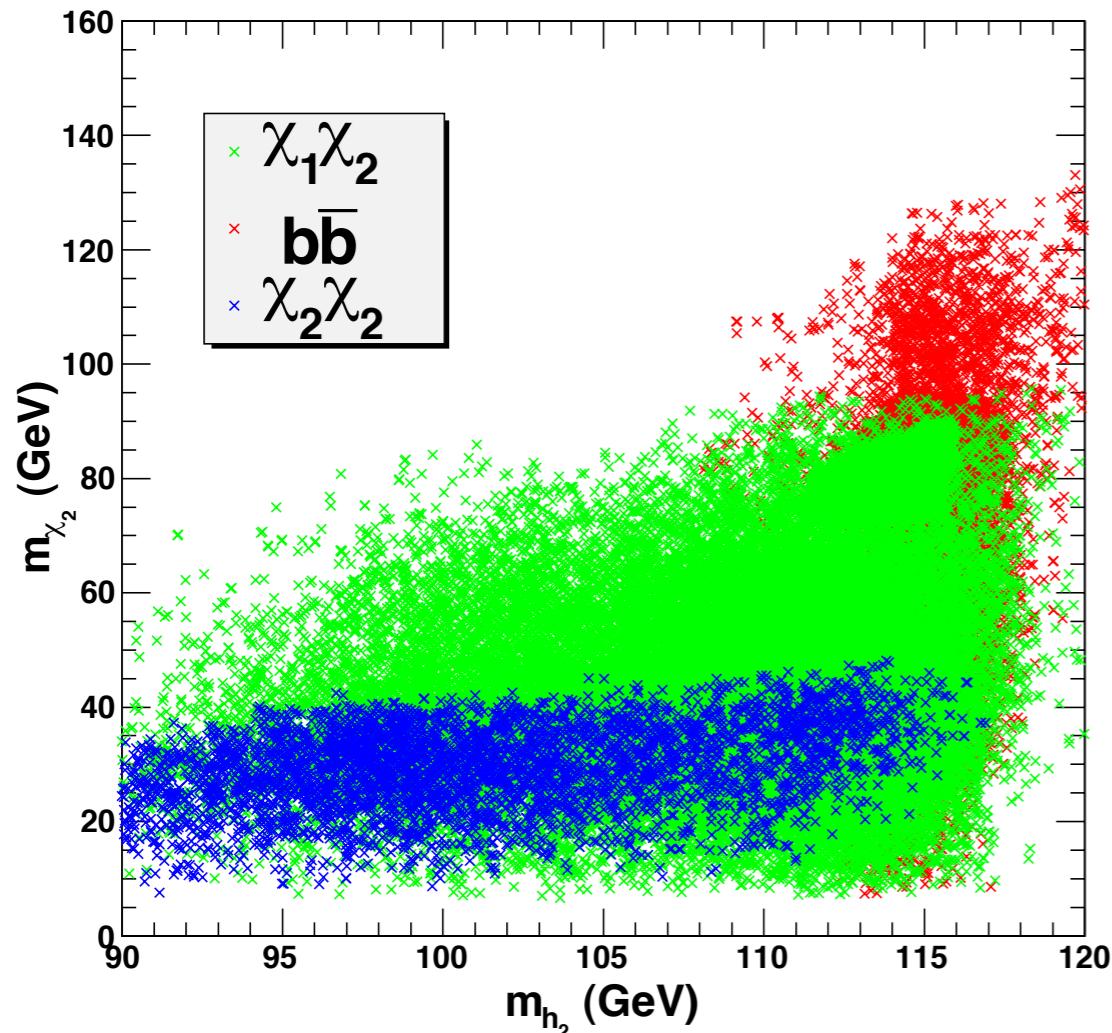
We convert the 2 μ 2 τ constraints to 4 μ constraints, using the relation

$$\begin{aligned} BR(h_1 \rightarrow 2\tau) &= BR(h_1 \rightarrow 2\mu) \\ &\times \left(\frac{m_\tau}{m_\mu} \right)^2 \left(\frac{1-4m_\tau^2/m_{h_1}^2}{1-4m_\mu^2/m_{h_1}^2} \right)^{3/2} \end{aligned}$$

19



Q1: How Does the SM-like Higgs Decay ?

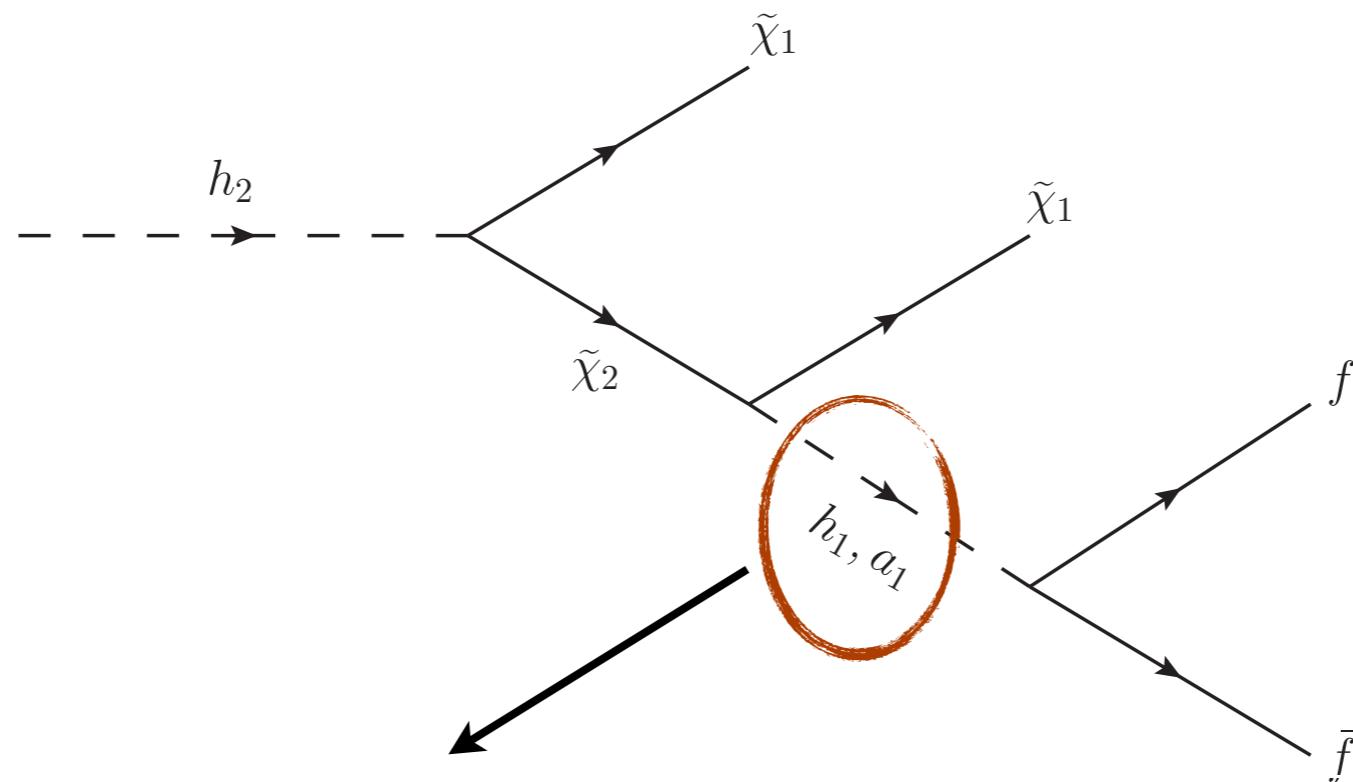


- ☒ $b\bar{b}$ mode becomes dominant sometimes, but not generic.
- ☒ As long as kinematically allowed, $h_2 \rightarrow \chi_1 \chi_2$ becomes dominant (χ_2 is bino-like)
- ☒ Not very hard because χ_1 is light
- ☒ h_2 with a mass ~ 100 GeV is allowed; stop quark mass can be below 300 GeV

20



Decay Topology of a SM-like Higgs Boson



On-shell resonance

21



Q2: How to Search for the SM-like and the light Higgs Bosons ?

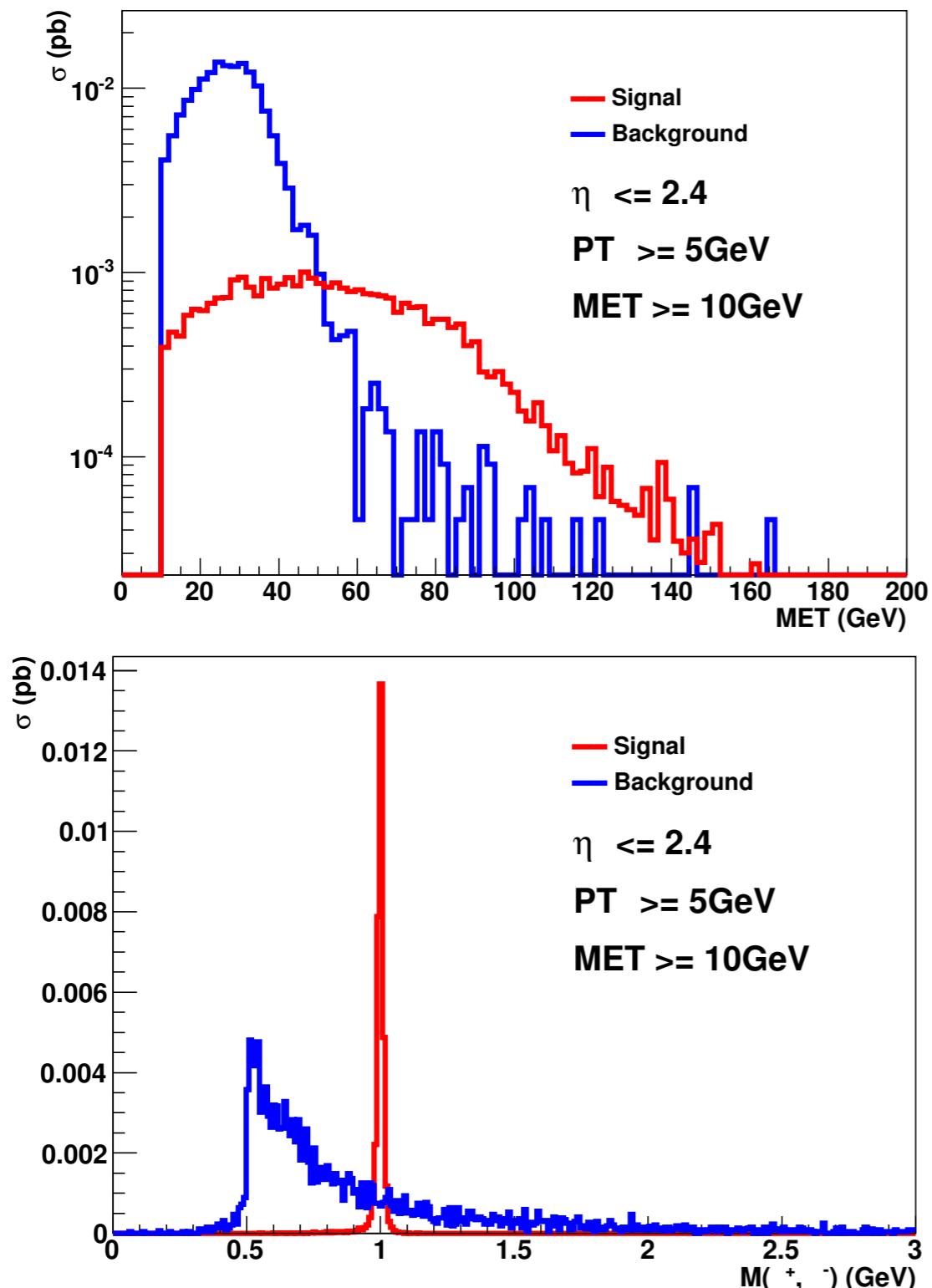
- ☒ The non-standard decays will necessarily change the searching strategies of both the SM-like (h_2) and the light Higgs bosons (a_1, h_1)
- ☒ For the searches of a SM-like Higgs boson

$h_2 \rightarrow \chi_1 + \chi_2$, with $\chi_2 \rightarrow \chi_1 + h_1, a_1$.

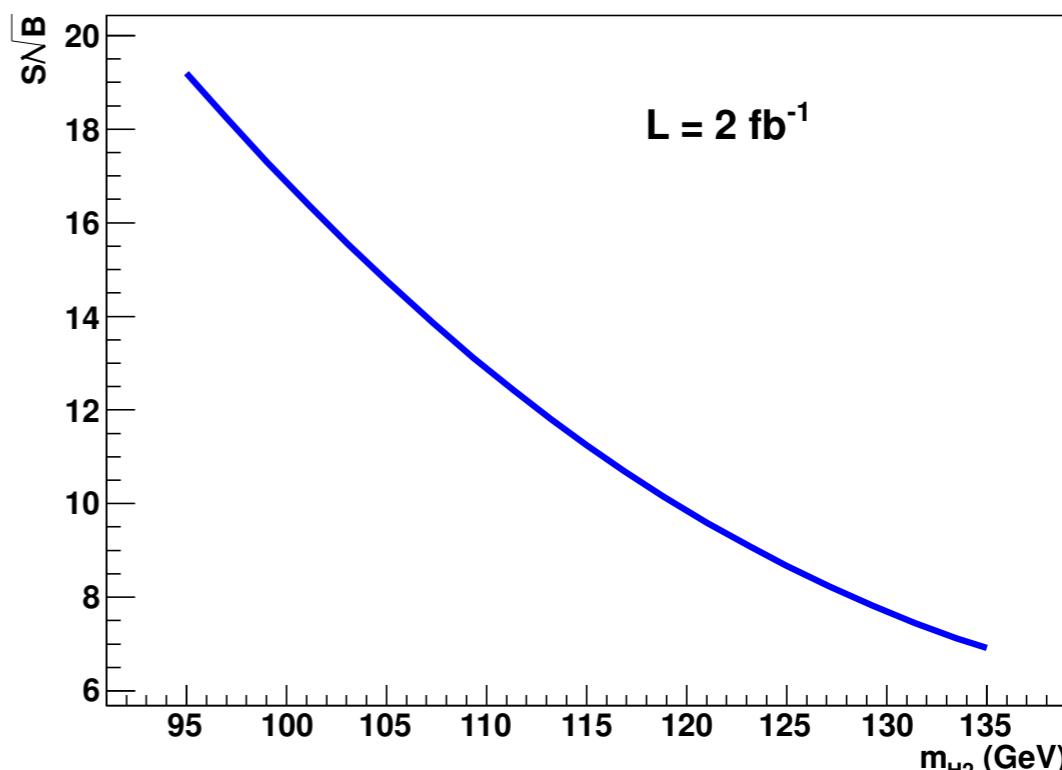
- ☒ Multiple possibilities - how h_2 is produced? + how h_1, a_1 are decayed? (In progress, T.L., J.R. Huang, S.F. Su, L.T. Wang, C. Wagner and F. Yu)
- ☒ A complementary way - searching for light Higgs bosons directly, in supersymmetric cascaded decays (In progress, S.F. Su, T.L. Wang and C. Wagner)



Some Preliminary Results at the 7 TeV LHC



- ☒ One example: $pp \rightarrow w h_2, w \rightarrow \mu \nu \mu \nu$ and $h_2 \rightarrow 2\chi_1 + h_1, h_1 \rightarrow \mu \mu$
- ☒ Dominant background: $w + \text{photon}^*$
- ☒ Two useful cuts: (1) missing energy cut, (2) mass window cut



23



- ❖ What is the ``Dark Light Higgs'' Scenario
- ❖ Supersymmetric Light Dark Matter
- ❖ Non-standard Higgs Physics
- ❖ Conclusions

24



Conclusions

- A benchmark scenario (DLH) in the NMSSM possessing novel Higgs and DM properties
- The lightest Higgs scalar and pseudoscalar and the lightest neutralino are light, all of order 10 GeV or below
- Provides a supersymmetric light DM scenario characterized by large spin-independent direct detection $\chi e\bar{e}$
- h_2 is SM-like, whose light Higgs pair decays are generically suppressed. However, Supersymmetric non-standard decays become dominant more often.
- Searching strategies of both the SM-like and the light Higgs bosons need to be dramatically changed.
- Interesting implications for electroweak phase transition in the early Universe (see Nasheen R. Shah's talk after me)

An aerial photograph of a coastal town, likely Santa Barbara, California. The town is built on a hillside overlooking a large blue ocean. In the foreground, there's a mix of residential buildings with red roofs, green lawns, and some industrial or institutional buildings with white walls and blue roofs. A winding river or stream flows through the town, eventually emptying into the ocean. The ocean has white-capped waves crashing against the shore. In the background, a range of mountains is visible under a clear blue sky.

Thank you!



Long List of Experimental Constraints

☒ Collider (LEP + Tevatron)

- (1) Direct searches for new particles at LEP;
- (2) Direct searches for new particles at the Tevatron;
- (3) Electroweak precision observables;
- (4) muon anomalous magnetic moment

.....

☒ Flavor physics and meson decay:

- (1) Constraints from B-system;
- (2) Constraints from K-system;
- (3) Constraints from charm system;
- (4) Upsilon decays

.....

☒ Cosmology:

- (1) Dark matter relic density;
- (2) Dark matter direct detection;
- (3) Dark matter indirect detection, cosmic rays;
- (4) Big bang nucleosynthesis, Cosmic Microwave Background Radiation

.....



Cut Flow

- $|\eta_{\mu^\pm}| \leq 2.4, PT_{\mu^\pm} \geq 5GeV;$
- $|\eta_{\mu 3}| \leq 2.4, PT_{\mu 3} \geq 5GeV;$
- $MET \geq 30GeV;$
- $0.9GeV \leq M(\mu^+, \mu^-) \leq 1.1GeV.$

N_{PreSel}	4215	ϵ_{PreSel}	42.15%
N_η	4215	ϵ_η	42.15%
N_{PT}	3897	ϵ_{PT}	38.97%
N_{MET}	3137	ϵ_{MET}	31.37%
$N_{m_{\mu\mu}}$	3079	$\epsilon_{m_{\mu\mu}}$	30.79%

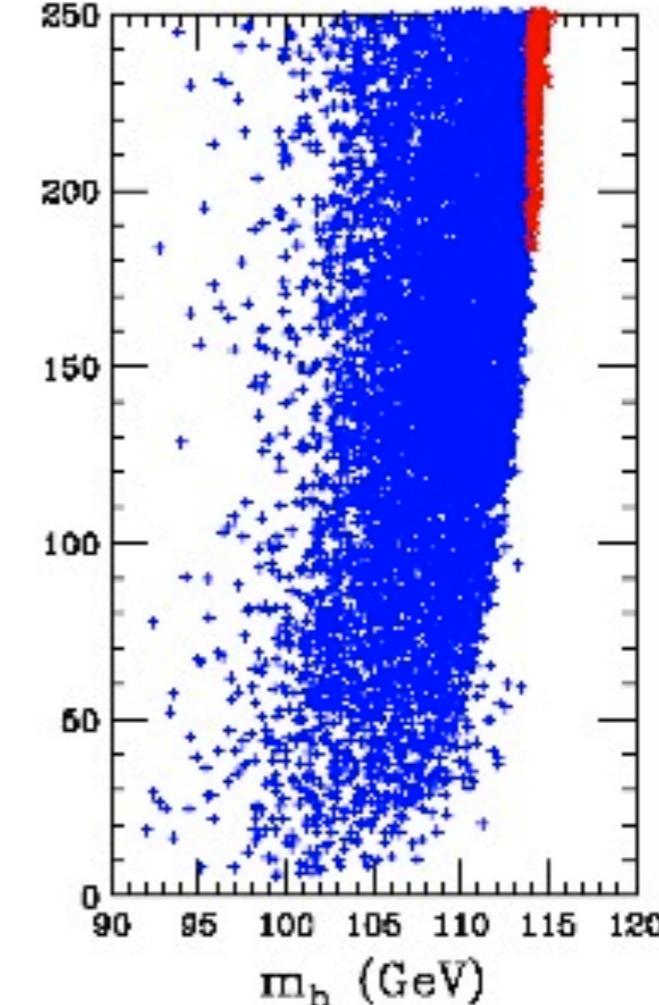
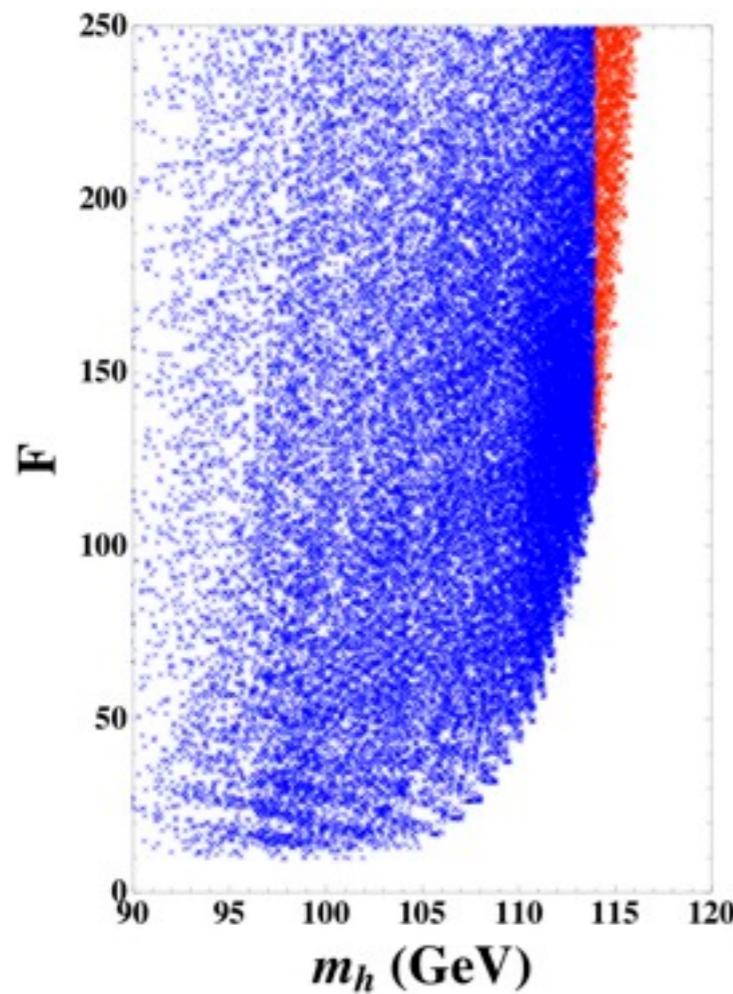
28



Quantitatively Description

$$F = \text{Max}_a F_a \equiv \text{Max}_a \left| \frac{d \log m_Z}{d \log a} \right|$$

``a'' denotes soft parameters and mu parameter at GUT scale
(G. Kane and S. King, Phys.Lett.B451 (1999))



Preliminary figure. T.L., C. Wagner
and Z. Hao. In progress

R. Dermisek and J. Gunion,
Phys.Rev.Lett.95 (2005)